A CASCADED INVERTER FOR SINGLE-PHASE GRID CONNECTED PHOTOVOLTAIC SYSTEM

RANJITA KATNAL (109EE0300)

Department of Electrical Engineering
National Institute of Technology Rourkela

A CASCADED INVERTER FOR SINGLE-PHASE GRID CONNECTED PHOTOVOLTAIC SYSTEM

A CASCADED INVERTER FOR SINGLE-PHASE GRID CONNECTED PHOTOVOLTAIC SYSTEM

A Thesis submitted in partial fulfillment of the requirements for the degree of

Bachelor of Technology in "Electrical Engineering"

By

RANJITA KATNAL (109EE0300)

Under guidance of

Prof. SOMNATH MAITY

Department of Electrical Engineering

National Institute of Technology

Rourkela-769008 (ODISHA)

May-2013

DEPARTMENT OF ELECTRICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ODISHA, INDIA-769008

CERTIFICATE

This is to certify that the thesis entitled "**A Cascaded Inverter for Single-phase Grid-connected Photovoltaic System**", submitted by **Ranjita Katnal (Roll. No. 109EE0300)** in partial fulfilment of the requirements for the award of **Bachelor of Technology** in **Electrical Engineering** during session 2012-2013 at National Institute of Technology, Rourkela. A bonafide record of research work carried out by them under my supervision and guidance.

The candidates have fulfilled all the prescribed requirements.

The Thesis which is based on candidates' own work, have not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a bachelor of technology degree in Electrical Engineering.

Place: Rourkela

Dept. of Electrical Engineering
National institute of Technology
Rourkela-769008

Prof.Somnath Maity
Assistant Professor

ACKNOWLEDGEMENTS

On the submission of my thesis report of "A cascaded Inverter for single-phase grid-connected system", I would like to extend my gratitude and sincere thanks to my **supervisor Prof. Somnath Maity**, Asst. Professor of the Department of Electrical Engineering, NIT Rourkela for his essential advice, support and constant motivation at every step of this project in the past year. I am indebted to him for his esteemed guidance starting from formation of the problem statement to final derivation and insights for the solution.

I also extend my gratitude to the researchers and engineers whose hours of toil has produced the papers and theses that I have utilized in my project.

Ranjita Katnal

B.Tech (Electrical Engineering)

<u>Dedicated to</u>

<u>My beloved parents</u>

ABSTRACT

The Photo Voltaic (PV) energy system, used in this project, is a very new concept in use, which is gaining immense popularity due to increasing importance to research on alternative sources of energy over depletion of the conventional fossil fuels all around the world. The systems which are being developed extract energy from the sun in the most efficient manner and suit them to the available loads without affecting their performance.

In this project, The design and control issues associated with the development of a 1.8 kW prototype single-phase grid-connected photovoltaic system a multilevel cascaded inverter are discussed in this project. For the current controller a ramp time zero average current error control algorithm combined with an optimized cyclic switching sequence is suggested. Simulation results have been presented to demonstrate the suitability of the control method. Simulation results exhibits improved performance under the presence of harmonics and the studied system is modeled and simulated in the MATLAB/Simulink.

CONTENTS

CHAPTER 1

INTRODUCTION

CHAPTER 2

PV ARRAY CHARACTERISTICS

CHAPTER-3

SYSTEM DESCRIPTION

CHAPTER-4

SIMULATION RESULTS

CHAPTER-5

CONCLUSION AND FUTURE WORK

LIST OF FIGURES

LIST OF TABLES

CHAPTER **1**

Introduction

1.1 MOTIVATION:

In the past, various different inverter topologies have been suggested or are currently used for low power, single-phase grid-connected photovoltaic (PV) Systems. A common technology in use is a full-bridge inverter in combination with a Line-frequency transformer. The transformer, however, is not an essential requirement and Inverters without transformers offer several advantages. A recent European Market survey [1] shows that transformerless Inverters are advantageous with respect to efficiency, cost, weight, embodied energy, and size. Table 1.1 shows the results of a comparison of single-phase inverters for grid-connected PV systems in the power range 1±2 kW. Thirty inverters were compared, of which seven were transformerless (23 with transformer). The gures for weight and price are normalized to the inverters rated power and especially the price difference between the two inverter types is impressive (the transformerless type being nearly 25% cheaper).

Besides advantageous transformerless concepts, multilevel inverters also promise good solutions, since these inverters have the capability to produce “stepped” output voltage waveforms. These waveforms approach the sinusoidal waveform better than those produced by conventional full-bridge inverters. Multilevel inverters therefore require less filter effort on the AC side, which makes the inverter cheaper, lighter and more compact. In order to generate the “multi-level” (stepped) output voltage waveform, different DC voltage levels are necessary. These can be provided by dividing a PV array into appropriate sub-arrays.

Based on a comparison of different multilevel topologies [2] a cascaded inverter has been identified as a suitable topology for transformerless, single-phase, grid- connected PV systems [1]. As part of a joint research project between the Centre for Renewable Energy Systems Technology Australia (CRESTA) and Power Search Ltd a 1.92 kW prototype system is currently under development.

INVERTER TYPE	MAX. EFFICIENCY %	WEIGHT Kg/kW	PRICE AS$/W
With transformer	93.1	16.1	1.95
Transformerless	95.9	12.3	1.47

Table 1.1 : Comparison of 30 inverters (23 with transformer, 7 transformerless) for single-phase, grid-connected PV systems

This project tries to report on the investigation of different grid current control methods for the cascaded inverter, and to present an optimized cyclic switching sequence to operate the eight inverter switches [3].

1.2 PV ENERGY GENERATION CONCEPTS:

1.2.1 Grid-Connected Applications*:*

In this mode of solar power generation, the solar arrays are used in large capacities of the order of MW for the generation of bulk power at the solar farms, which are coupled through an inverter to the grid and feed in power that synchronises with the conventional power in the grid. The grid connected solar power operates at 33KV and at 50 Hz frequency through inverter systems, whereas the solar farms generate the average power output of about 5MW each. Owing to quite high power generations, the batteries are not used to store power as in the case of isolated power generation for economic concerns. 53 grid-connected solar projects were selected up to the end of 2010 comprising of total capacity of 704MW.

1.2.2 Stand Alone Applications*:*

This mode of energy generation from solar energy consists of systems which are not connected to the grid, i.e. off-grid applications (captive power). It is done especially in the places where there is acute scarcity of electricity derived from conventional sources. These stand-alone systems have a solar array coupled with a power conditioning device such as an inverter that converts the power from DC to AC to suit the load requirements, such as home power, and a battery to store the solar energy harnessed during the day which is to be consumed in the absence of solar energy. These decentralised systems of PV arrays operate at parameters below 33KV and 50Hz through the inverter. However, the higher capacities of the order of KW are usually sold to the grid to get paid with attractive tariffs. The heating systems concentrate the solar rays on heating water which can be used for cooking, washing, power generation, etc.

1.3 ORGANISATION OF THESIS:

The thesis is organised into five chapters including the chapter of introduction. Each chapter is different from the other and is described along with the necessary theory required to comprehend it.

Chapter2 deals with PV Array Characteristics and its modelling. First, the solar cell is described and various material technologies available for construction of solar cells are seen. The equivalent mathematical modelling of the solar cell is made after studying various representations and simplification is made for our purpose. The IV characteristics curve for the equivalent model is studied in MATLAB-Simulink environment using the equation corresponding to that model. Also, the concept of MPPT is studied theoretically to understand the role of converter in extracting the maximum power from the solar array with the help of MPPT controller. Also inverters are discussed here and MOSFET .

Chapter3 describes the system description and its various functions. The theory about Filters is discussed. Why LCL filter is used and its design is also discussed here. Grid synchronisation is also studied here. Current controller types are discussed and also voltage controllers. Why the active power and reactive need to be controlled is also discussed.

Chapter4 shows the practical implementation of the system and all the simulation results obtained.

Chapter5 gives the conclusion of the project.

CHAPTER 2

PV Array Characteristics

2.1 INTRODUCTION:

Photovoltaics allow the consumers to generate electricity in a clean, reliable and quiet manner. Photovoltaics are often abbreviated as PV. Photovoltaic cells combine to form photovoltaic systems. Photovoltaic cells are devices that convert light energy or solar energy into electricity. As the source of light is usually the sun, they are often referred to as solar cells. The word photovoltaic is derived from “photo,” meaning light, and “voltaic,” which refers to production of electricity. Hence photovoltaic means “production of electricity directly from sunlight.”[4] Usually, a PV system is composed of one or more solar PV panels, an AC/DC power converter (also known as an inverter), and a rack system that holds the solar panels, and the mountings and connections for the other parts. A small PV system can provide energy to a single consumer, or to isolated devices like a lamp or a weather device. Large grid-connected PV systems can provide the energy needed to serve multiple customers [5].

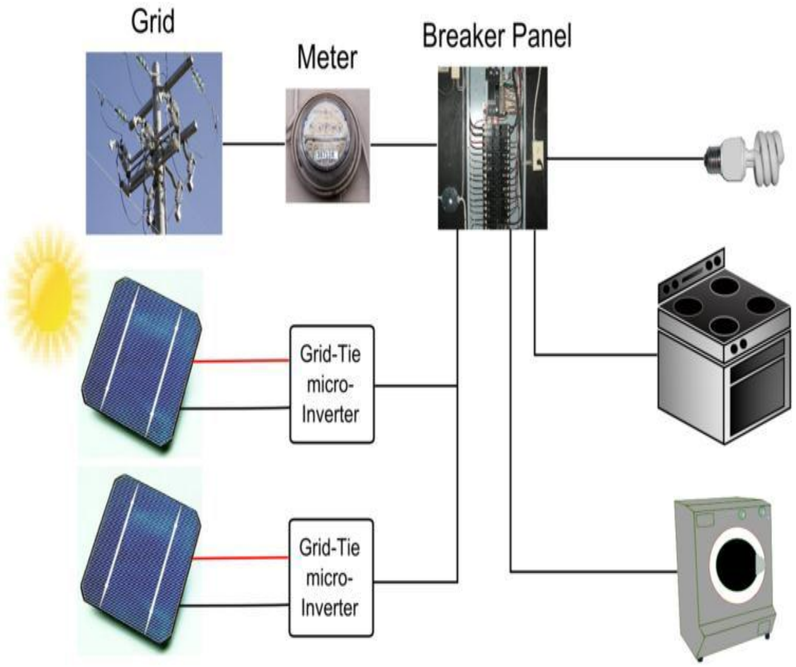

Fig 1: Schematic diagram of a simple photovoltaic system

2.2 PHOTOVOLTAIC MODULES:

A single individual solar cell has a very low voltage (usually ca. 0.5V). Hence, several cells are wired together in series giving rise to a "laminate". The laminate is then assembled into a protective weatherproof casing, thus creating a photovoltaic module or a solar panel.

Modules may be then strung together to form a photovoltaic array. The electricity generated can either be stored, put into direct use (island/standalone plant), fed into a big electricity grid powered essentially by central generation plants (grid-connected/grid-tied plant), or fed into a small grid after combining with one or many domestic electricity generators (hybrid plant). Depending on the application type, the rest of the system known as balance of system or "BOS" consists of several components. The BOS is dependent on the load profile and the type of system.

2.3 PHOTOVOLTAIC ARRAY:

The power production capacity of single module is seldom enough to satisfy the requirements of a home or a business. Hence, the modules are linked together to form an array [6]. The DC power produced by the modules is converted into alternating current that can provide power to lights, motors, and other loads. Most PV arrays use an inverter to achieve this. The modules in a PV array are series connected to obtain the requisite voltage following which the individual strings are parallel connected to allow the system to generate more current. A *photovoltaic array* (or *solar array*) is a linked collection of solar panels. Solar panels are typically measured under STC (standard test conditions) or PTC (PVUSA test conditions), and are given in watts. Panel ratings generally range from around 100 watts to over 400 watts. The array rating is the sum of all the panel ratings. Its unit is watts, kilowatts, or megawatts [7].

2.4 PV ARRAY MODELLING:

The solar cell arrays or PV arrays are usually constructed out of small identical building blocks of single solar cell units. They determine the rated output voltage and current that can be drawn for some given set of atmospheric data. The rated current is given by the number of parallel paths of solar cells and the rated voltage of the array is dependent on the number of solar cells connected in series in each of the parallel paths.

A solar cell is basically a p-n junction fabricated in a thin substrate of semiconductor. When exposed to sunlight, some electron-hole pairs are created by photons that carry energy higher than the band-gap energy of the semiconductor. The figure shows the typical equivalent circuit of a PV cell.

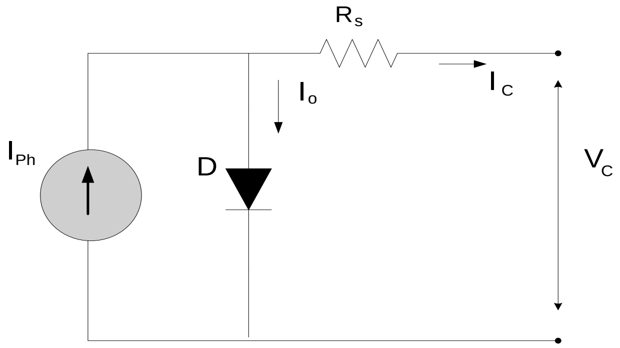

Fig 2: PV cell single diode equivalent circuit diagram

The typical I-V output characteristics of a PV cell are shown by the following equations:

Module Photo current (I_{ph}):

$$I_{ph} = [I_{scr} + k_i(T - 298)]G \div 1000 \quad (1)$$

Module reverse saturation current Irs :

$$I_{rs} = I_{scr} / e^{(\frac{qV_{oc}}{N_s}KAT)} - 1 \quad (2)$$

Module saturation current I_0:

$$I_o = I_{rs} = \left[\frac{T}{T_r}\right] e^{\frac{qE_{gv}}{BK(\frac{1}{T_r}-\frac{1}{T})}} \quad (3)$$

The current output of PV module I_c:

$$I_c = N_p I_{ph} - \text{N } I_o[e^{\frac{q(V_c+I_{ph})}{(NAKT)}} - 1] \quad (4)$$

where

V_c is output voltage of PV module(V)

T_r is the reference temperature = 289K

T is the module operating temperature

A is an ideality factor = 1.6

K is Boltzmann constant = 1.3805 * 10-23 J/K

q is electron charge

R_s is the series resistor of PV module

I_{scr} is the PV module short circuit current = 1.1A

K is the short circuit current temperature coefficient=0.0017A/C

G is the PV module illumination = 1000W/m2

E_{go} is the band gap for silicon = 1.1eV

V_o is the open circuit voltage = 18V

Different I-V and P-V characteristics are obtained by the PV array model for different solar radiations keeping the temperature constant at 25 degrees Celsius. As the irradiation is increased the current output increases significantly, resulting in an increase in the output power. On increasing the temperature, the output current increases marginally whereas the output voltage decreases to a great extent which results in a net reduction in the output power. To conclude, we can say that the output current of the PV module is influenced by a change in irradiation, whereas the output voltage is influenced by temperature variations. Therefore, in order to extract the maximum power from the solar panel and to track the changes in environmental conditions, an MPPT is used.

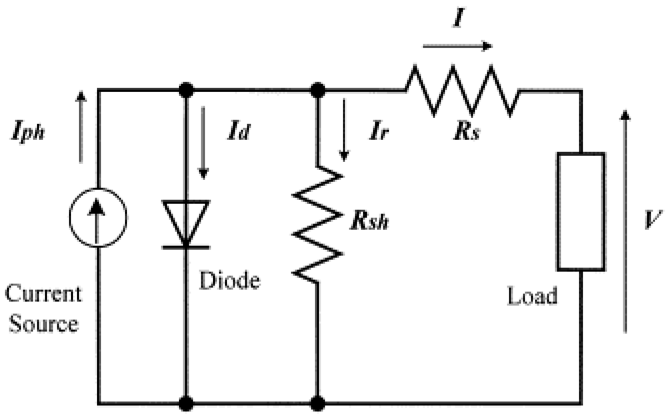

Fig 3: Overall model of a PV cell

The solar array operating point is determined by three factors - the load, the ambient temperature and the irradiation on the array. When the load current increases, the voltage drops. When temperature increases, the output power reduces due to an increase in the resistance across the cell. When irradiation levels increase, the output power increases as more number of photons are able to knock out electrons leading to greater current flow and recombination.

2.5 INVERTERS:

The function of a solar or PV inverter is to convert the variable direct current (DC) output of a PV solar panel into a utility frequency alternating current (AC) which can be fed to a commercial electrical grid or can be used by a local, off-grid electrical network. It is an important component in a PV system that allows the use of regular commercial devices. Solar inverters perform special functions adapted for use with photovoltaic arrays, including MPPT and anti-islanding protection. They are used in induction heating, stand by air-craft power supplied etc. Phase controlled converters when operated in the inverter model are called line commuted inverters. The dc power input given to the inverter is obtained from an existing power supply network or from a rotating alternator through a rectifier in a fuel cell, battery, photovoltaic array, or an MHD generator [8].

The classification of solar inverters can be done as follows:

1. **Stand alone inverters** - A **stand-alone inverter** is a power inverter that converts direct current (DC) into alternating current (AC) independent of a utility grid. These inverters are often used to convert DC produced by various renewable sources of energy like small wind turbines or solar panels, into AC used in homes and small industries. These types of inverters are commonly used in residential buildings in remote locations which do not have a utility grid and are powered by sources of renewable energy.

Fig 4: A typical stand-alone inverter

2. **Grid-tie inverters** - A **grid-tie inverter** (**GTI**) or **synchronous inverter** is a special type of power inverter which converts direct current (DC) into alternating current (AC) and feeds it to an existing electrical grid. GTIs are commonly used to convert DC produced by various sources of renewable energy, such as small wind turbines or solar panels, into AC used in homes and businesses. The technical name for a GTI is "grid-interactive inverter". Grid-interactive inverters do not find use in standalone applications where there is unavailability of utility power. When a period of overproduction occurs, power is routed to the power grid and sold to a local power company. During periods of insufficient power production, the reverse occurs and power is purchased from the power company.

Fig 5: Inverter for grid connected PV

3. **Battery backup inverters** - are special inverters that can take energy from a battery, manage the charge on the battery through an on board charger, and export excessive energy to the utility grid. These inverters have the capability to supply AC energy to selected loads during a decrease in utility service, and are required to have anti-islanding protection.

2.6 MOSFETS:

MOSFET is an acronym for metal–oxide–semiconductor field-effect transistor. It is a transistor that is used to amplify electronic signals and which can act as a switch too. The MOSFET is essentially a four-terminal device. The four terminals are the source (S), gate (G), drain (D), and body (B) terminals. The body (or substrate) of the MOSFET is generally connected to the source terminal by internal short-circuiting, making it a three-terminal device like other field-effect transistors [9]. Hence, only three terminals appear in electrical diagrams. The MOSFET is presently the most commonly used transistor in both digital and analog circuits, though the bipolar junction transistor much more common once.

In enhancement mode MOSFETs, a voltage drop across the metal oxide induces a conducting channel between the source and drain contacts due to the field effect. The term "enhancement mode" means an increase in conductivity with increase in oxide field which adds carriers to the channel, also called as the inversion layer. The channel can contain electrons (called an nMOSFET or nMOS), or holes (called a pMOSFET or pMOS), opposite in type to the substrate. Hence, nMOS is made with a p-type substrate, and pMOS with an n-type substrate. In the depletion mode MOSFET the channel consists of carriers in a surface impurity layer of opposite type as the substrate, and the conductivity is decreased by application of a field that depletes carriers from this surface layer.

2.6.1 MODES OF OPERATION:

For an enhancement-mode, n-channel MOSFET, the three operational modes are:

2.6.1.1 When $V_{GS} < V_{TH}$:

Where V_{GS} gate-to-source is bias and V_{TH} is the threshold voltage of the device and $V_{GS} < V_{TH}$, the transistor is switched OFF and there is no conduction between the drain and the source.

During weak inversion the current changes exponentially with V_{GS} and is approximately given by:

$$I_D \approx I_{DO}\, e^{(V_{GS}-V_{TH}) \div nV_T} \qquad (5)$$

Where, $I_{DO} is\ the\ current\ at\ (V_{GS} = V_{TH})$, the thermal voltage $V_T = KT/q$ and the thermal or slope factor n is defined as:

$$\text{n} = 1 + C_{D/C_{OX}} \qquad (6\ )$$

C_D = capacitance of the depletion layer and C_{OX}= capacitance of the oxide layer.

In a long-channel device, the drain voltage is independent of the current once $V_{DS} \gg V_{TH}$ but as channel length is reduced it becomes dependent in a complex way that depends on the device geometry and the channel and junction doping.

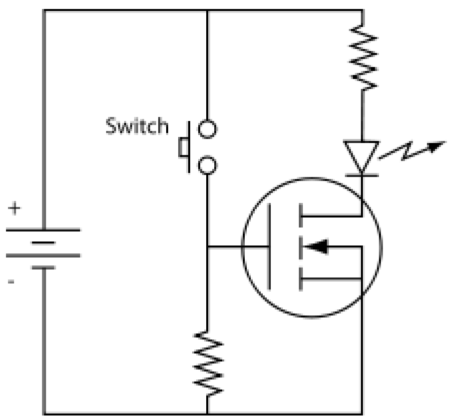

Fig 6: Schematic diagram of a MOSFET

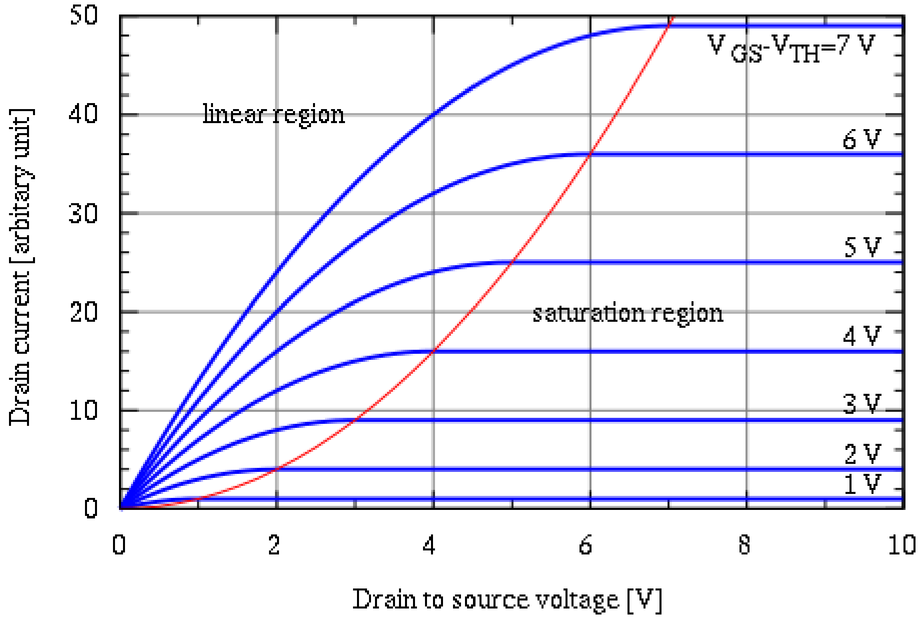

Fig 7: The graphical relational between the Drain current and drain to source voltage

2.6.1.2 A Triode mode or linear region (also known as the ohmic mode):

When $V_{GS} > V_{\mathrm{th}}$ and $V_{DS} < (V_{GS} – V_{\mathrm{th}})$

In this mode the transistor is turned on, and a channel is created which allows current to flow between the drain and the source. The MOSFET acts and performs like a resistor which is controlled by the gate voltage relative to the source and drain voltages. Since the voltage between transistor gate and source (V_{GS}) exceeds the threshold voltage (V_{TH}), it is known as Overdrive voltage. The current from drain to source is given as:

$$I_{D=} \mu_n C_{ox} W/L((V_{GS} - V_{th})V_{DS} - V_{DS}^2/2) \qquad (7)$$

Where μ_n is the charge-carrier effective mobility, W is the gate width, L is the gate length and C_{ox} is the gate oxide capacitance per unit area.

2.6.1.3 Saturation or active mode:

When $V_{GS} > V_{TH}$ and V_{DS} $(V_{GS} – V_{\mathrm{th}})$

The transistor is in ON mode, and a channel is created, which allows current to flow between the drain and the source. Since the drain voltage is higher than the gate voltage, the electrons space out, and conduction is through a broader channel now. The onset of this region is also known as pinch-off and is called so, so as to indicate the lack of channel region near the drain. The drain current now shows weak dependence on the drain voltage and is primarily controlled by the gate–source voltage. It is approximately given as:

$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (V_{GS} - V_{TH})^2 \, (1 + \lambda(V_{DS} - V_{DSsat})) \quad (8)$$

$$g_m = \frac{2I_D}{V_{GS} - V_{th}} = \frac{2I_D}{V_{OV}} \quad (9)$$

A key design parameter for MOSFETs is the MOSFET output resistance r_{out} given by:

$$r_{out} = \frac{1}{\lambda I_D} \quad (10)$$

r_{out} is the inverse of g_{ds} where, I_D is the expression in saturation region. If λ is taken to be zero, an infinite output resistance of the device results that leads to unrealistic circuit predictions, particularly in analog circuits.

2.7 IV CHARACTERISTICS OF SOLAR CELL:

The output characteristics of a solar cell determine the power output that can be drawn from the cell under varying load demands and changing atmospheric conditions. The output voltage is a function of the ambient temperature and decreases with an increase in the temperature due to a reduction in the width of the PN junction. The output current is a function of the solar insolation as photons are able to knock out more number of electrons. The output current increases with an increase in the irradiation incident on the surface of the cell, the temperature being constant.

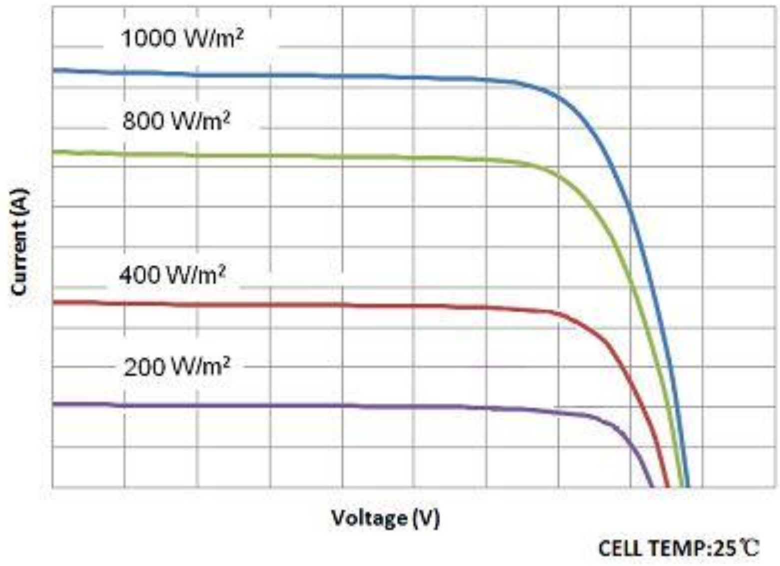

Fig 8: I-V Characteristics at cell temperature of 25°C

2.8 MAXIMUM POWER POINT TRACKING:

The environmental conditions under which a solar power system shall operate can be broad, as shown in the I-V curves. The current-voltage relationship of a solar array varies throughout the day, as it changes with respect to environmental conditions such as irradiance and temperature. In terrestrial applications, Low Irradiance and Low Temperature (LILT) condition represents the morning condition when the sun just rises. A High Irradiance and High Temperature (HIHT) condition might reflect a condition near high noon in a humid area. High Irradiance and Low Temperature (HILT) condition can reflect a condition with healthy sunlight in the winter. Finally, a condition near sunset can be described by Low Irradiance and High Temperature (LIHT) condition. For space applications, LILT characterizes a deep space mission or aphelion period, while HIHT condition is when satellite orbits near the sun (perihelion).

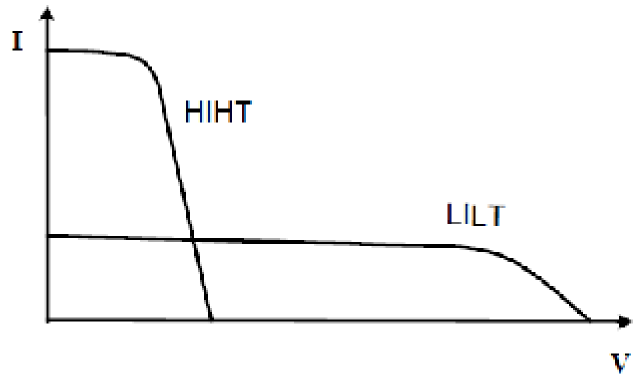

Fig 9: I-V characteristics under wide operating conditions

For a uniformly illuminated array, there is only one single point of operation at which maximum power will be extracted from the array. In a battery charging system where the load seen by the solar modules is a battery connected directly across the solar array terminals, the operating point is determined by the battery's potential. This operating point is generally not the ideal operating voltage at which the modules are able to produce their maximum available power.

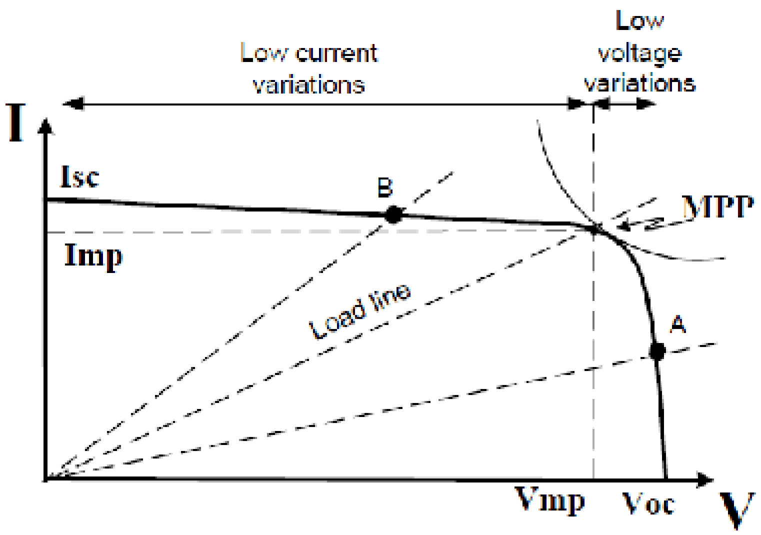

Fig 10: Direct Coupled Method

In the direct coupled method [13], the solar array output power is delivered directly to the loads, as in figure 10. To match the MPPs of the solar array as closely as possible, it is essential to choose the solar array I-V characteristic according to the I-V characteristics of the load. A general idea for the power feedback control is to measure and maximize the power at the load terminal which assumes that the maximum power of the array equals the maximum load power. However, the power to the load gets maximized, not the power from the solar array. The direct-coupled method cannot automatically track the MPPs of the solar array when the temperature or solar radiation changes. The load parameters or solar array parameters must be carefully selected so as to account for the changes in the solar radiation or temperature.

To be able to extract the maximum power from the solar array and to track the changes due to the environment, a maximum power point tracking should be implemented. Devices that perform the requisite function are known as Maximum Power Point Trackers, also called MPPTs or trackers. A tracker consists of two basic components, as shown in figure 11, a switch-mode converter and a control with tracking capability. The switch-mode converter forms the core of the entire supply. The converter allows energy to be drawn at a particular potential, stores it as magnetic energy in an inductor, and then releases the same at a different potential. Either high-to-low (buck converter) or low-to-high (boost) voltage converters can be constructed by setting up the switch-mode section in various topologies. The goal of a switch-mode power supply is to provide a constant output voltage or current. In power trackers, the whole aim is to provide a fixed input voltage and/or current, so that the array is kept at the maximum power point, while allowing the output voltage to match the battery voltage.

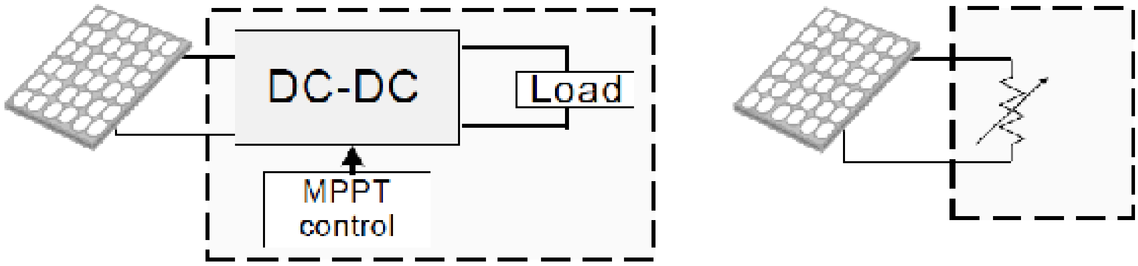

Fig 11: Basic components of a maximum power pointer tracker

When properly applied, MPPT control can help to prevent the collapse of the array voltage at very high load demands, particularly when the supply is to a constant-power type load. One of the proper approaches is to operate the system in a solar array voltage regulation mode where the array voltage is clamped to a commanding set point, V_{mp}, which is dynamically updated by the MPPT control circuit. The MPPT control processes feedback signals, such as the array current and voltage, to determine a proper direction in which the operating point is to be moved. Eventually, this continuously updated set point will fluctuate around the voltage corresponding to the array peak power point. By adjusting the operating point of the array to the point V_{mp}, power output of the array can be maximized, and the most fruitful use of the solar array may be obtained.

For a system without MPPT, the voltage will quickly collapse to zero. This phenomenon can be understood from the I-V characteristic of a solar array. The flatness of the I-V curve on the left of the MPP implies that a small incremental increase in current demand leads to large voltage change. A system with MPPT avoids the voltage collapse by keeping the operating point near the MPP. On the I-V curve, the operating point corresponding to the maximum-power point is around the kneel region. Therefore, unlike other power systems with stiff voltage sources, power conversion from solar arrays with MPPT requires more robust designs due to the inherent risks of an array voltage collapse under peak load demand or severe changes in the array characteristics.

The location of the MPP of an I-V characteristic is unknown and must be located. A number of MPPT control algorithms/methods have been proposed. In subsequent sections, these algorithms will be reviewed.

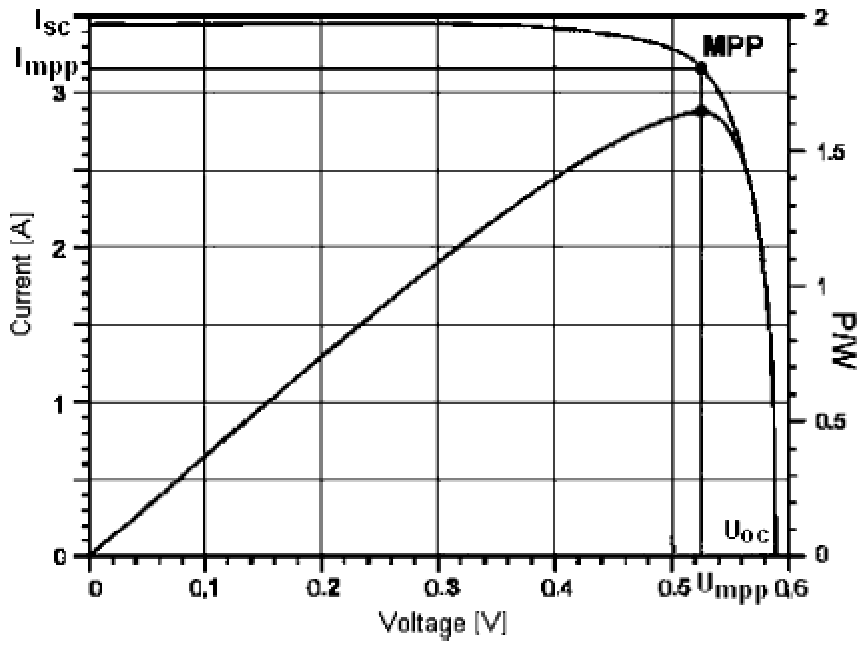

Fig 12: Typical characteristic curve of a solar cell.

2.8.1 1NCREMENTAL CONDUCTANCE METHOD

In the incremental conductance method, the array terminal voltage is adjusted according to the MPP voltage it is based on the incremental and instantaneous conductance of the PV module.

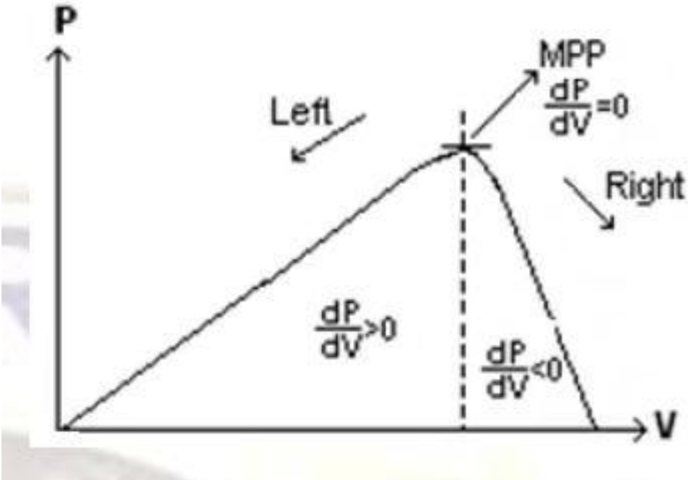

Fig 13: Basic idea of incremental conductance method on a P-V Curve of solar module

The above figure shows that the slope of the P-V array power curve is zero at The MPP, is positive and increasing to the left of the MPP and negative and decreasing to the right of the MPP. The basic equations are given as:

$dI/\ dV = -\ I\ /\ V$ - at MPP (11)

$dI\ /\ dV > -\ I\ /\ V$ - left of MPP (12)

$dI\ /dV < -\ I\ /\ V$ - Right of MPP (13)

Where I and V are P-V array output current and voltage respectively. The left hand sides of the equations represent incremental conductance of P-V module and the right hand sides represent the instantaneous conductance. When the incremental conductance is equal to the negative of the instantaneous output conductance, the solar array will operate at the maximum power point.

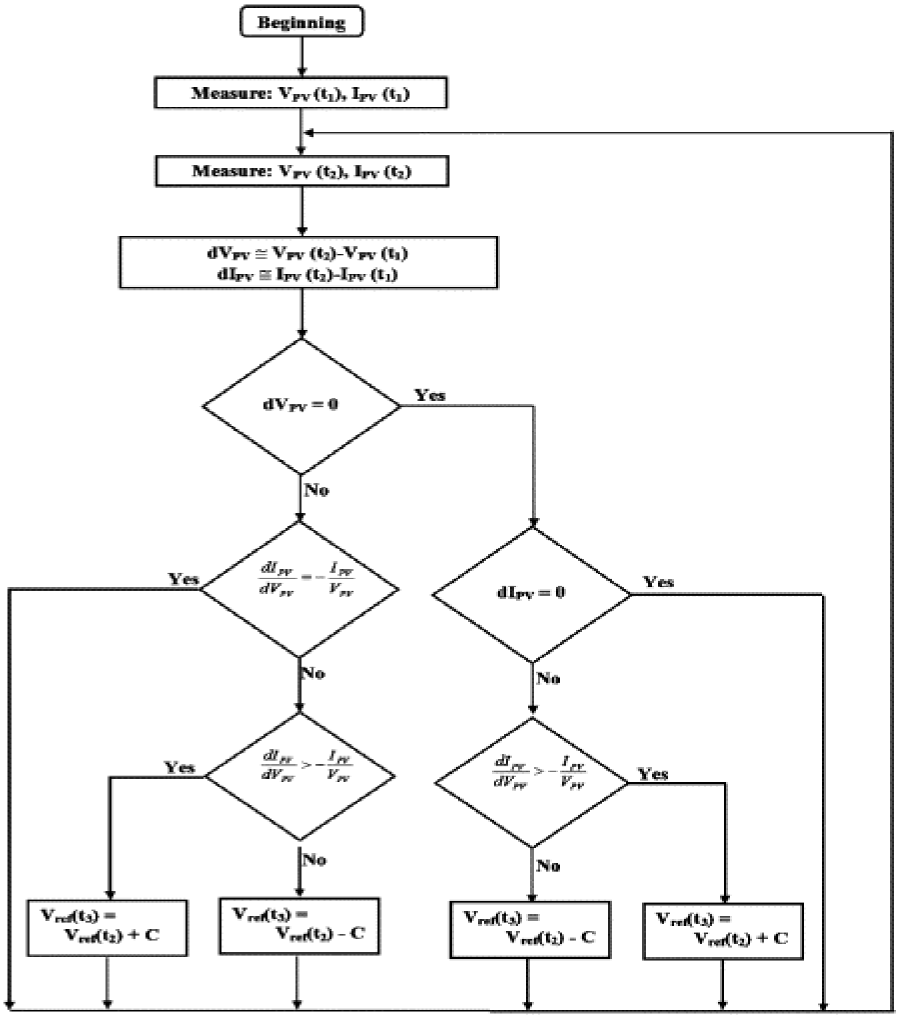

Fig 14: flowchart of ICM method

2.9 CONCLUSION:

The Photovoltaic cell has been studied here by considering its equivalent circuit representation. The IV characteristics of the mathematical model of solar cell are studied and the relationship between the output voltage and output current from the cell is plotted in the graph using MATLAB-Simulink source. The effect of temperature on IV characteristics of solar cell has also been studied. With the help of this study and the results, how the concept of Maximum Power Point Tracking can be used to obtain the maximum power from the solar cell and how to control the operating point is clearly understood.

CHAPTER **3**

SYSTEM DESCRIPTION

3.1 INTRODUCTION:

The cascaded system discussed in this paper has various systems attached to it. It is a complex system and has various levels of working resulting in the final output we require. The system uses no transformers but only cascaded inverters which add to the advantages resulting in higher efficiencies and better cost-effectiveness. The cascaded inverter comprises of two conventional full-bridge topologies with their AC outputs connected in series. Each bridge has the capacity to create three different voltage levels at its AC output allowing for an overall five-level AC output voltage (see Fig 15). One period (20 ms for a 50 Hz signal) can be divided into six sections, each representing a different operational mode of the inverter.

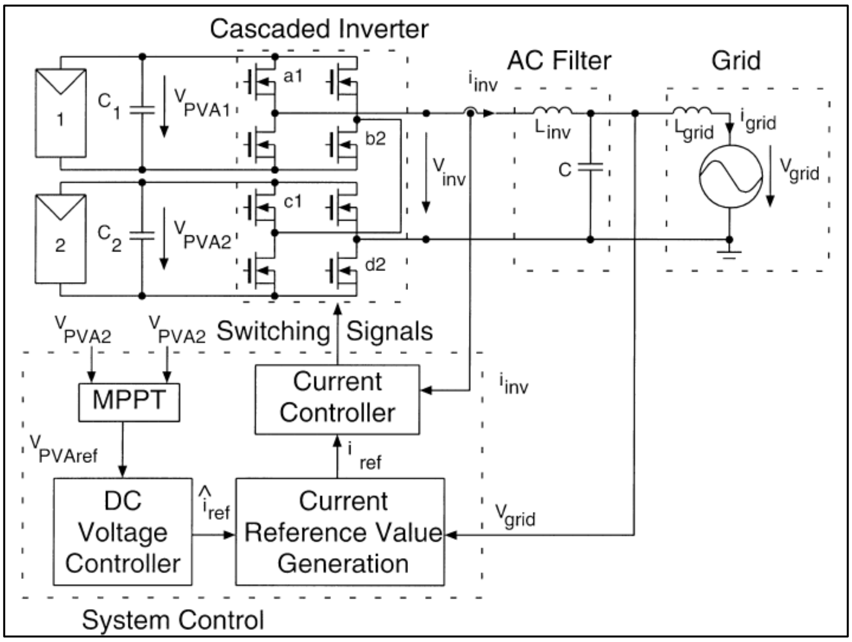

Fig15: overall system used

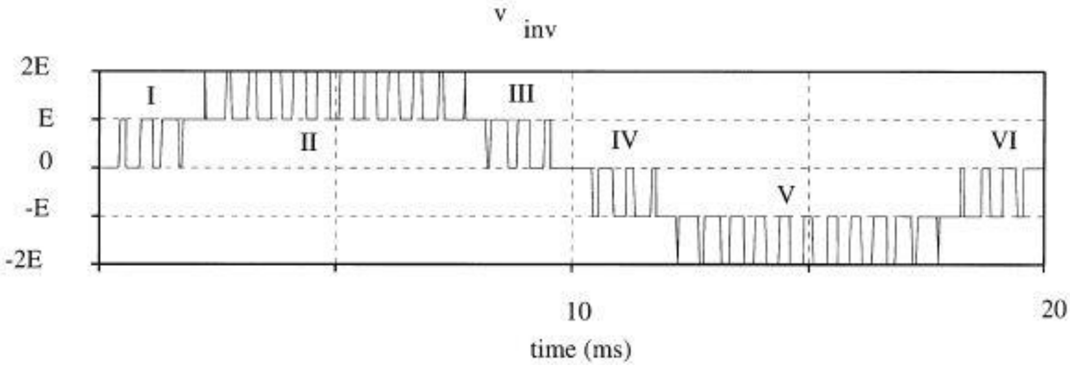

Fig 16: Example of the cascaded inverter output voltage. The periods I±VI indicate the different modes the inverter operates in.

3.2 FILTERS:

In order to eliminate the current harmonics around the switching frequency, the grid-connected inverter for renewable energy source, an output low-pass filter is required. Ideally, filters that have low cut-off frequency and high attenuation at the high switching frequency do a much better job at eliminating switching ripples efficiently.

There are 3 types of filters :

1. L FILTER
2. LC FILTER
3. LCL FILTER

3.2.1 L FILTERS:

Firstly, though a single inductor L-filter is quite popular and simple to use, it has low attenuation and high inductance. The voltage drop across the inductor results in poor system dynamics, thereby leading to a long-time response. When L-filters are used, the inverter switching frequency must have a high value in order to sufficiently attenuate the harmonics [12].

Secondly, since lower attenuation of the inverter switching components is achieved by L-filters, a shunt element is required in order to further attenuate the switching frequency components. A capacitor is chosen to generate low reactance at the switching frequency and to produce high magnitude impedance within the control frequency range.

3.2.2 LC FILTERS:

The LC-filter is best suited to such configurations where the load impedance across the capacitor is relatively high at and above the switching frequency. The capacitance should be high to reduce cost and losses but a very high value of capacitance is not advisable since problems such as high reactive current fed on capacitor at the fundamental frequency, inrush current, possible resonance at the grid side, etc. can occur in the system. If a system is connected to the grid through an LC-filter, the resonance frequency varies over time as the inductance value of the grid varies [13].

3.2.3 LCL FILTERS:

In comparison to the previous filter topologies, LCL-filters can provide a better attenuation at the inverter switching frequency. LCL-filters can produce a better decoupling between the filter and the grid impedance. LCL-filters are also found to be able to give a good attenuation ratio even with small C and L values.

However, several constraints have to be considered in designing the three-order LCL-filter, such as the current ripple through inductors, the resonance phenomenon, the total filter impedance, the reactive power that the capacitor absorbs, the current harmonics attenuation at switching frequency etc [14].

3.2.3.1 LCL FILTER DESIGN:

The LCL-filter's equivalent circuit diagram is depicted in Fig.18 and its equivalent model is shown in Fig.19, where V_1 and V_2 are inverter and grid voltage respectively, L_1, L_2, R_1, R_2 are the filter inverter-side and grid-side inductor and its equivalent resistors respectively. A damping resistor R_3 is placed in series with capacitor C_f.

Basing on the equivalent circuit diagram of the LCL-filter, the transfer function of LCL filter using the inverter current as feedback can be derived by assuming that the value of R_1 and R_2 are quite small so as to be neglected:

$$G(s) = \frac{i_2(s)}{v_1(s)} \frac{R_3 C_f\ s+1}{L_1 L_2 C_f s^3 + (L_1+L_2) R_3 C_f s^2 + (L_1+L_2) s} \qquad (14)$$

The resonant frequency is $w_{res} = \frac{\sqrt{L_1+L_2}}{\sqrt{L_1 L_2 C_f}}$ (15)

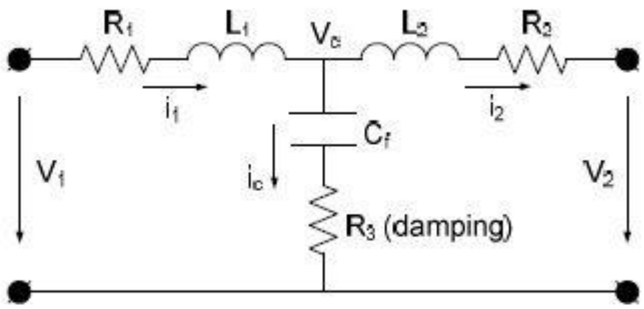

Fig 17: Equivalent circuit diagram

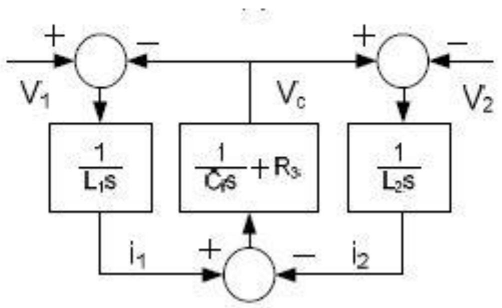

Fig 18: Model of LCL Filter

There are some limits on the parameter values while designing such a filter:

1.The total per unit inductance should be less than 0.1 because inductances result in the AC voltage drop during operation. To avoid this, a higher dc-link voltage will be required which will result in higher switching losses.

2.The capacitance is limited by the reactive power factor (normally this factor is less than 5%).

3.The resonant frequency should be in range: $10w_0 \leq w_{res} \leq \frac{w_{sw}}{2}$ to avoid resonance problems, where $w_0$the utility frequency (rad/s) is, w_{res} is the resonant frequency (rad/s) and w_{sw} is the switching frequency (rad/s).

3.3 GRID SYNCHRONISATION:

The number of PV installations has an exponential growth, mainly due to the governments and utility companies that support programs that focus on grid-connected PV systems [15], [16].

In a general structure distributed system, the input power is transformed into electricity by means of a power conversion unit whose configuration is closely related to the input power nature. The electricity produced can be delivered to the local loads or to the utility network, depending where the generation system is connected.

One important part of the distributed system is its control.The control tasks can be divided into two major parts:

1. Input-side controller: Its main property is that it can extract the maximum power from the input source. Naturally, protection of the input-side converter is also important to be considered.
2. Grid – side controller: It performs the following:
    a. It controls the active power generated
    b. It controls the reactive power transfer between the DPGS and the grid
    c. Control of the dc-link voltage is done by the grid-side controller
    d. It ensures high quality of the injected power

The items listed above for the grid-side controller are the basic features this controller should have. In addition to the above, auxiliary services like voltage harmonic compensation, active filtering or local voltage and frequency regulation might be requested by the grid operator.

3.3.1 CONTROL STRUCTURES FOR GRID-CONNECTED SYSTEMS:

The control strategy which is applied to the grid-side converter consists primarily of two cascaded loops. Generally, there is a fast internal current loop, which is responsible for the regulation of the grid current, and an external voltage loop, which is responsible for the control of the dc-link voltage [17]-[22]. The current loop takes care of matters related to power quality and current protection. Hence, harmonic compensation and dynamics are important properties of the current controller. The dc-link voltage controller is designed so as to balance the power flow in the system.

The control of grid-side controller is based on a dc-link voltage loop cascaded with an inner power loop in place of a current loop so that the current injected into the utility network is controlled indirectly[23].

There are various types of control applications namely :

1.Synchronous Reference Frame Control :

Synchronous reference frame control, also called *dq* control, uses a reference frame transformation module, e.g., $abc \rightarrow dq$, to transform the grid current and voltage waveforms into a reference frame that rotates synchronously with the grid voltage. By such means, the control variables become DC values; thus, filtering and controlling can be achieved easily. In dq control, the dc-link voltage is controlled in accordance to the requisite output power. The output is the reference for the active current controller, whereas the reference for the reactive current is practically set to zero. In the case that the reactive power is to be controlled, a reactive power reference should be imposed on the system. The dq control is normally associated with Proportional-Integrals (PI) controller, since they have a satisfactory behavior when regulating dc voltages. The compensation capability of the low-order harmonics in the case of PI controllers is very poor, standing as a major drawback when using it in grid connected systems.

2. Stationary Reference Frame Control:

In this case, the grid currents are transformed into stationary reference frame using the abc $\rightarrow \alpha\beta$ module. Since the control variables are sinusoidal in this situation and due to the known drawback of PI controller in failing to remove the steady-state error when sinusoidal waveforms are to be controlled, employment of other controller types becomes necessary. Proportional resonant (PR) controller [24]-[27] gained a large popularity in the last decade in current regulation of grid-tied systems.
Characteristic to this controller is the fact that it achieves a very high gain around the resonance frequency, thus being able to eliminate the steady-state error between the controlled signal and its reference [26]. The width of the frequency band around the resonance point depends on the integral time constant Ki. A low Ki leads to a very narrow band, whereas a high Ki leads to a wider band.

3. *Evaluation of Control Structures*:

The necessity of voltage feed forward and cross-coupling term is the major drawback of the control structure implemented in synchronous reference frame. In addition to that the phase angle of the grid voltage is a must in this implementation. In the case of control structure implemented in a stationary reference frame, if PR controllers are used for current regulation, the complexity of the control becomes lower compared to the structure implemented in dq frame. In addition to that, the phase angle information is not a necessity, and filtered grid voltages can be used as templates for the reference current waveform.

In the case of control structure implemented in natural frame, the complexity of the control can be high if an adaptive band hysteresis controller is used for current regulation. A simpler control scheme can be achieved by implementing a dead-beat controller instead. Again, as in the case of stationary frame control, the phase angle information is not a must. Noticeable for this control structure is the fact that independent control of each phase can be achieved if grid voltages or three single phase PLLs are used to generate the current reference.

3.4 CURRENT CONTROLLER:

There are various methods to control the current. Controlled current is the inverter output current i_{inv}, which flows into the low-pass AC filter. Each controller generates a control signal which contains the information on whether i_{inv} needs to be increased or decreased. Together with the information on the mode of operation of the inverter, the control signal is required to derive the switching signals for the individual switches of the inverter.

The PI control method (see Fig. 20) is a common control method in grid- connected PV systems [28]-[29]. With this control method the frequency of the ripple on i_{inv} is the same as the frequency of the triangular waveform, which is constant, hence enabling better and easier AC filter design. However, simulation studies implementing the PI control method for the cascaded inverter showed that as the mode changes, the control is lost due to non-linear behavior of the system. The method has therefore not been investigated further for hardware implementation with the cascaded converter.

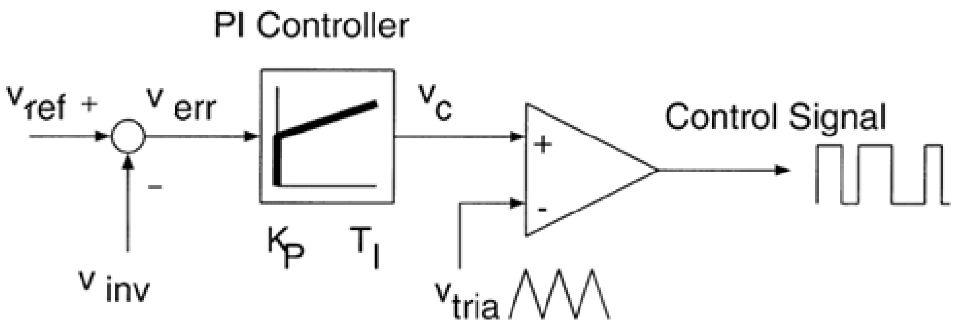

Fig 19: PI controller

The hysteresis control (see Fig.21) generates the control signal when exceeding a fixed magnitude. A disadvantage of this technique is the non-constant frequency in the ripple ofi_{inv}, which makes the AC filter design difficult and this method is therefore not implemented in the hardware of the discussed system.

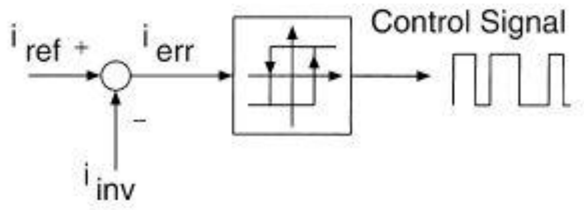

Fig 20: Hysteresis Controller

The Ramp time Zero Average Current Error (ZACE) control method (see Fig.21) forces the error of the current to be zero over one switching period. The basic principle of this control method is indicated in Fig. The controller detects the zero crossings of the current error and calculates the time until the next switching instant has to occur based on the desired control signal frequency. The control signal frequency is the same as the frequency of the ripple current on i_{inv}. The polarity of the current error and the desired control signal frequency are used to generate the control signal. The frequency of the ripple current is now within a narrow band. A controller using this method generating PWM frequencies up to 16 kHz has been realized in practice. The control method can be adapted to the multilevel inverter ensuring that the control is not lost during changes in the mode.

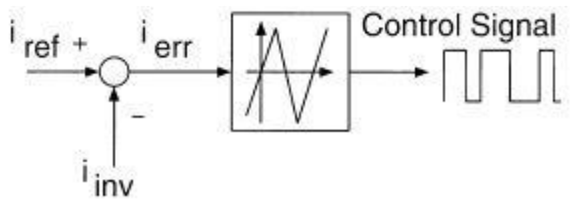

Fig 21: ZACE controller

3.4 DC VOLTAGE CONTROLLER:

METHOD 1:

DC voltage controller is used to provide the reference current value for the current controller. It is aimed at keeping the voltage constant on the DC side in normal condition or during grid faults or changes in the input power. The DC link voltage control is changed according to the balance of power exchanged by the converter.

The DC voltage loop is an outer loop while the current loop is an inner loop. The inner loop has been designed to achieve a short settling time in order to achieve a fast correction of the error. The outer loop can be design to be slower. Thus, the inner loop and the outer loop can be considered as decoupled and thus, they can be linearized.

The DC-link voltage is controlled by means of the converter side DC current and the plant is given by [30]:

$$G_{DC} = \frac{3\,S_d}{4}\frac{1}{C_{dc}s} \tag{16}$$

Where S_d is the switching steady state signal on d-axis which is averaged in the following computation to a value of 1 and C_{dc} is the value of the DC link capacitor.

The block diagram of the DC link controller is presented in Fig 22:

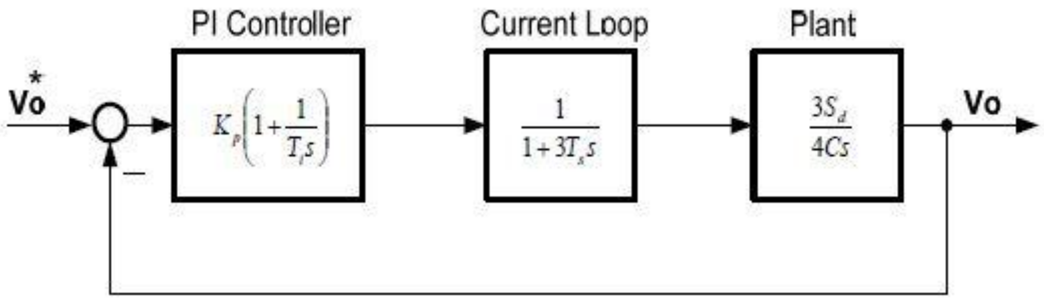

Fig 22 : Dc voltage loop

In The voltage control loop in S-domain is represented in the figure 22 which also includes the delay of the current loop and the DC link plant.

The transfer function in continuous domain for the PI controller is given by:

$$G_{PI} = K_P\left(1 + \frac{1}{T_1 s}\right) \tag{17}$$

To obtain the parameters according to this criterion, the phase margin can be imposed at 45°. Thus the controller parameter can be obtained as follows:

$$K_P = 0.33 \tag{18}$$

$T_1 = 0.0017$ (19)

a = 2.4 (20)

METHOD 2:

Since the primary objective of the controller is to regulate the DC bus voltage within a narrow band, a PI controller is the obvious choice. It may be noted that the voltage controller need not be very fast. It is, however desirable, that the transient undershoot or overshoot in the DC side is limited to a minimum, nominally within 5%. This is achieved by using the DC side load current as a feed-forward input to the voltage controller. The structure of the controller, along with the plant, is shown in Figure 23, where K_V is the voltage controller gain, T_V is voltage controller time constant, K_1 is the gain in the voltage sensing path, and T_1 is the time constant.

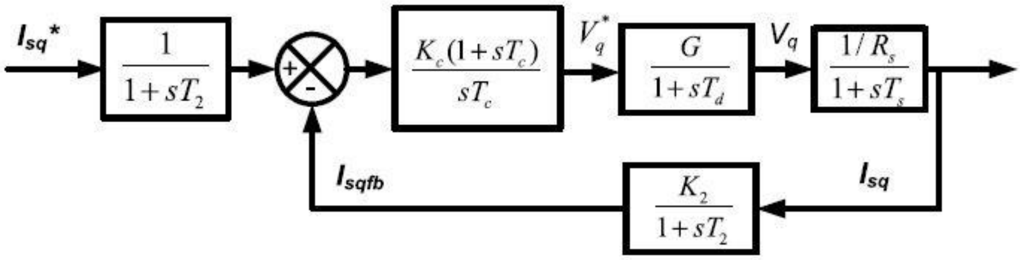

Fig 23: Modified current control loop

The outer voltage loop is much slower compared to the inner current loop. Hence, the transfer function of the current control loop has been approximated as:

$$\frac{I_{sq}s}{I_{sq}^{*}s} = \frac{1}{K_2}\frac{1}{(1+2\sigma s)} \quad (21)$$

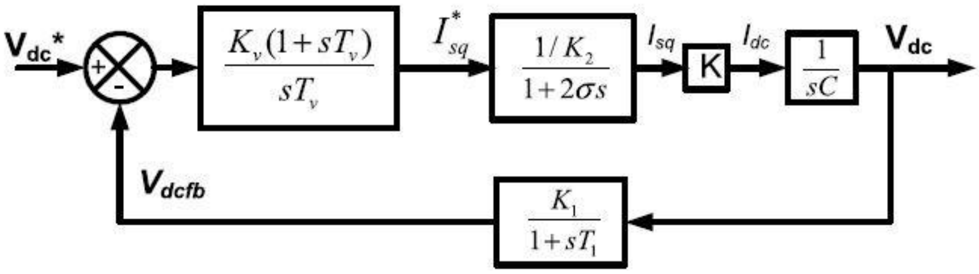

Fig 24: Voltage control loop.

3.5 CONCLUSION:

The various systems included in the cascaded system are discussed here. The various control algorithms involved In controlling current and voltage are also discussed. The filter and grid overview is also given and is found as why they are a necessity in the system.

CHAPTER 4

SIMULATION RESULTS

4.1 INTRODUCTION:

The practical implemental of the system is done and simulation results are obtained. PV system has to be studied to understand its source response, hence its I-V characteristics can be studied. The MPPT method is applied and results are obtained.

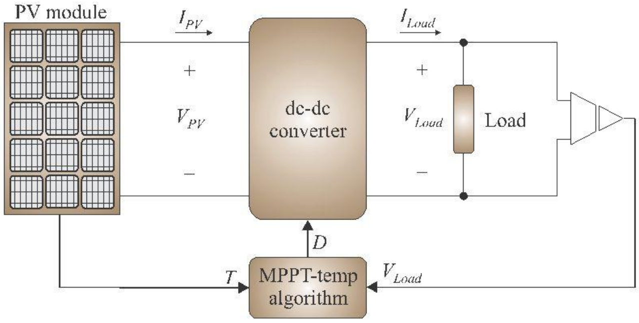

Fig 25: overall method

4.2 PV MODULE:

The PV array results are obtained in MATLAB using the following program.

```
T=28+273;

Tr1=40; % Reference temperature in degree Fahrenheit

Tr=((Tr1-32)* (5/3))+273; % Reference temperature in kelvin

S=[100 80 60 40 20]; % Solar radiation in mW/sq.cm

%S=70;

ki=0.00023; % in A/K

Iscr=3.75; % SC Current at ref. temp. in A

Irr=0.000021; % in A

k=1.38065*10^(-23); % Boltzmann constant

q=1.6022*10^(-19); % charge of an electron

A=2.15;

Eg(1)=1.166;
```

```
alpha=0.473;
beta=636;
Eg=Eg(1)-(alpha*T*T)/(T+beta)*q; % band gap energy of semiconductor used
cell in joules
Np=4;
Ns=60;
V0=[0:1:300];
c={'blue','red','yellow','green','black'};
for i=1:5
Iph=(Iscr+ki*(T-Tr))*((S(i))/100);
Irs=Irr*((T/Tr)^3)*exp(q*Eg/(k*A)*((1/Tr)-(1/T)));
I0=Np*Iph-Np*Irs*(exp(q/(k*T*A)*V0./Ns)-1);
P0 = V0.*I0;
figure(1)
plot(V0,I0,c{i});

hleg = legend('100 w/m^2','80 W/m^2','60 W/m^2','40 W/m^2','20 W/m^2');

axis([0 50 0 20]);
xlabel('Voltage in volt');
ylabel('Current in amp');
hold on;

figure(2)
plot(V0,P0,c{i});
hleg = legend('100 w/m^2','80 W/m^2','60 W/m^2','40 W/m^2','20 W/m^2');
axis([0 50 0 400]);
```

```
xlabel('Voltage in volt');

ylabel('Power in watt');

hold on;

figure(3)

plot(I0,P0,c{i});

hleg = legend('100 w/m^2','80 W/m^2','60 W/m^2','40 W/m^2','20 W/m^2');

axis([0 20 0 400]);

xlabel('Current in amp');

ylabel('Power in watt');

hold on;

end
```

The I-V curve obtained when the PV array is connected to an open circuit.

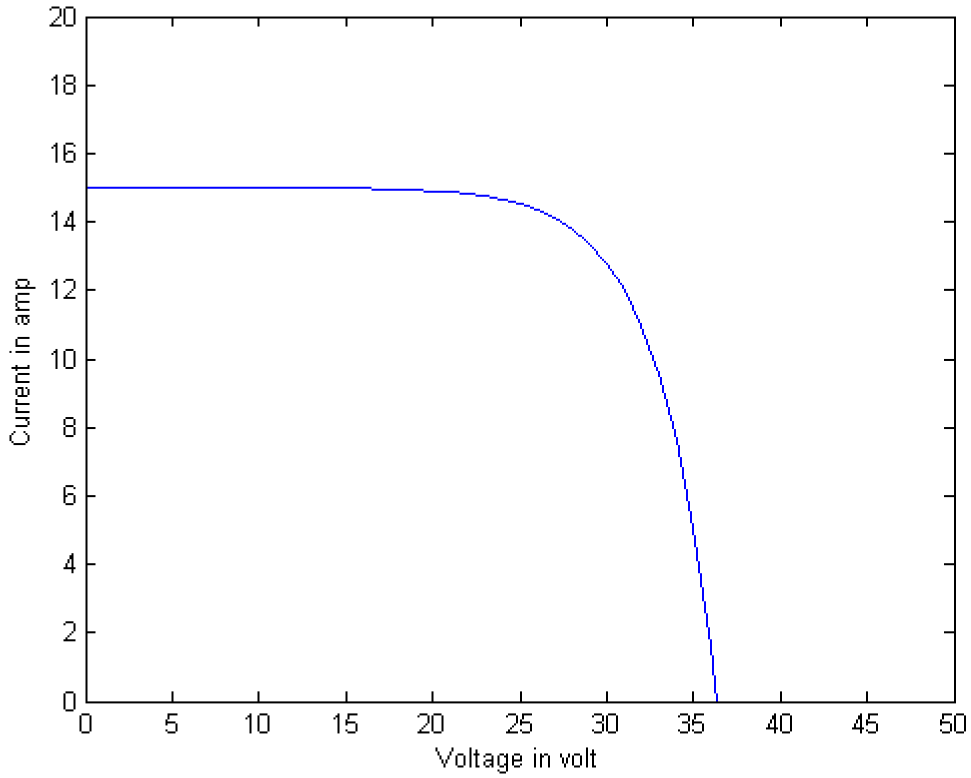

Fig 26: I-V curve

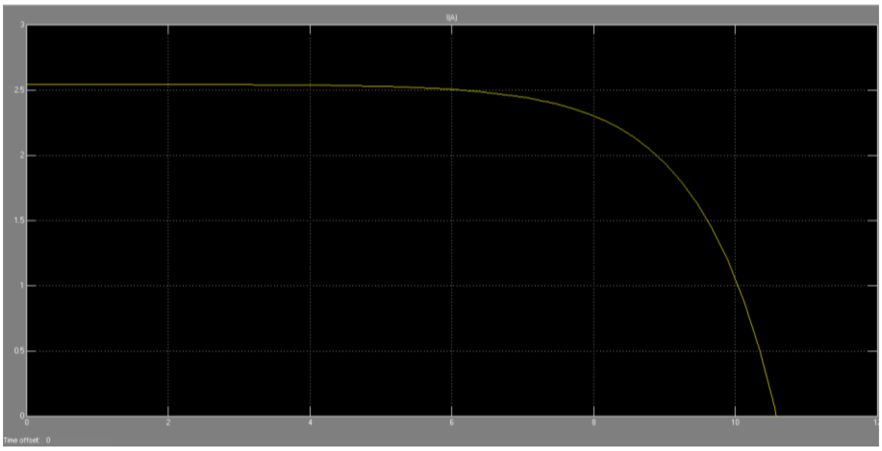

Fig 27: I-V curve in MATLAB SIMULINK

The P-V curve obtained by the PV array is as below.

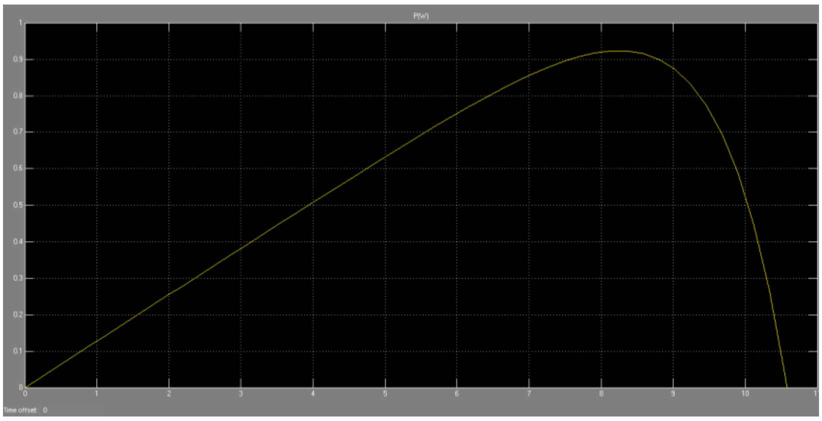

Fig 28: P-V curve

PV array output obtained is as follows:

The inverter output voltage is a obtained as given below.

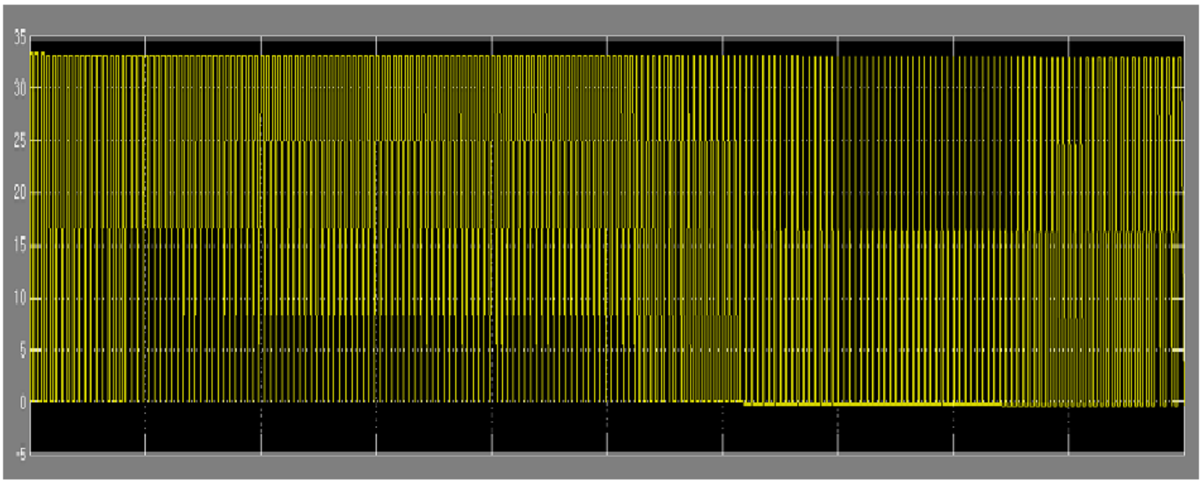

Fig 29: Inverter Output voltage

The DC bus voltage is obtained:

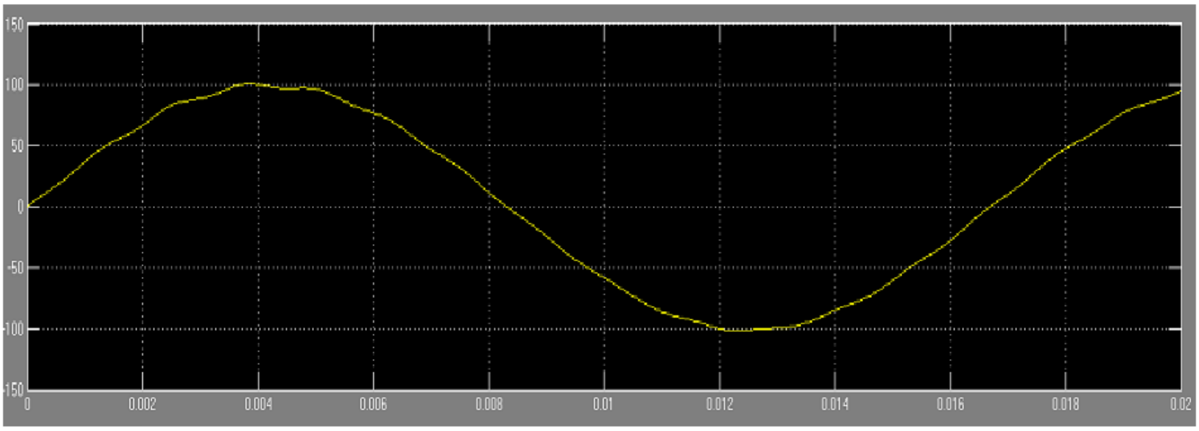

Fig 30: DC bus voltage

The PV array output is obtained as below:

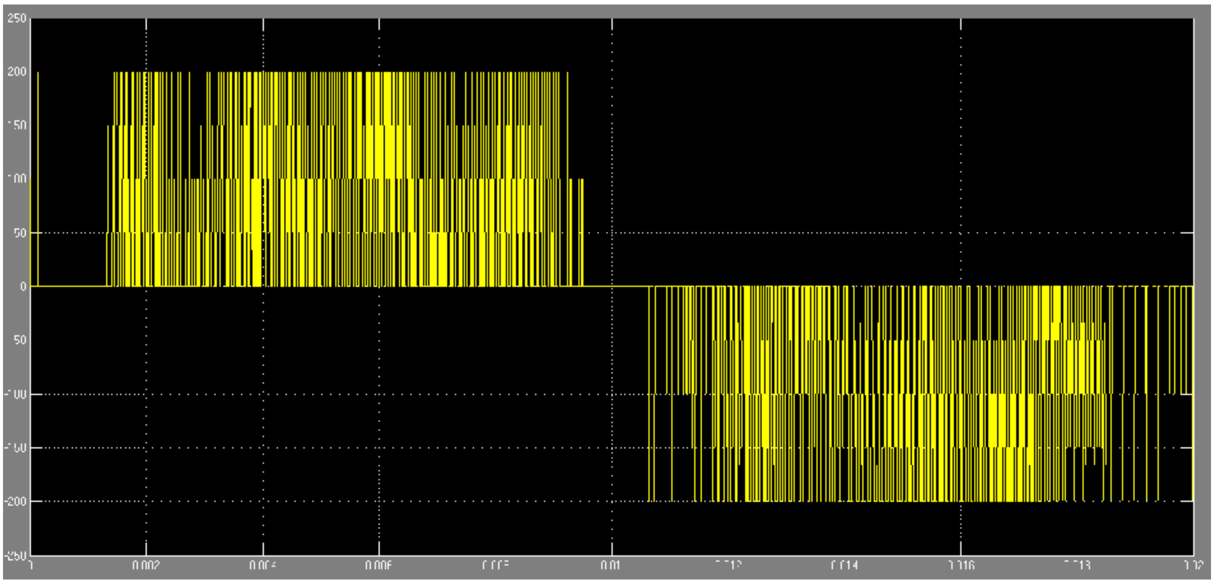

Fig 31: PV array output

3.3 OVERALL EXPERIMENTAL CIRCUIT:

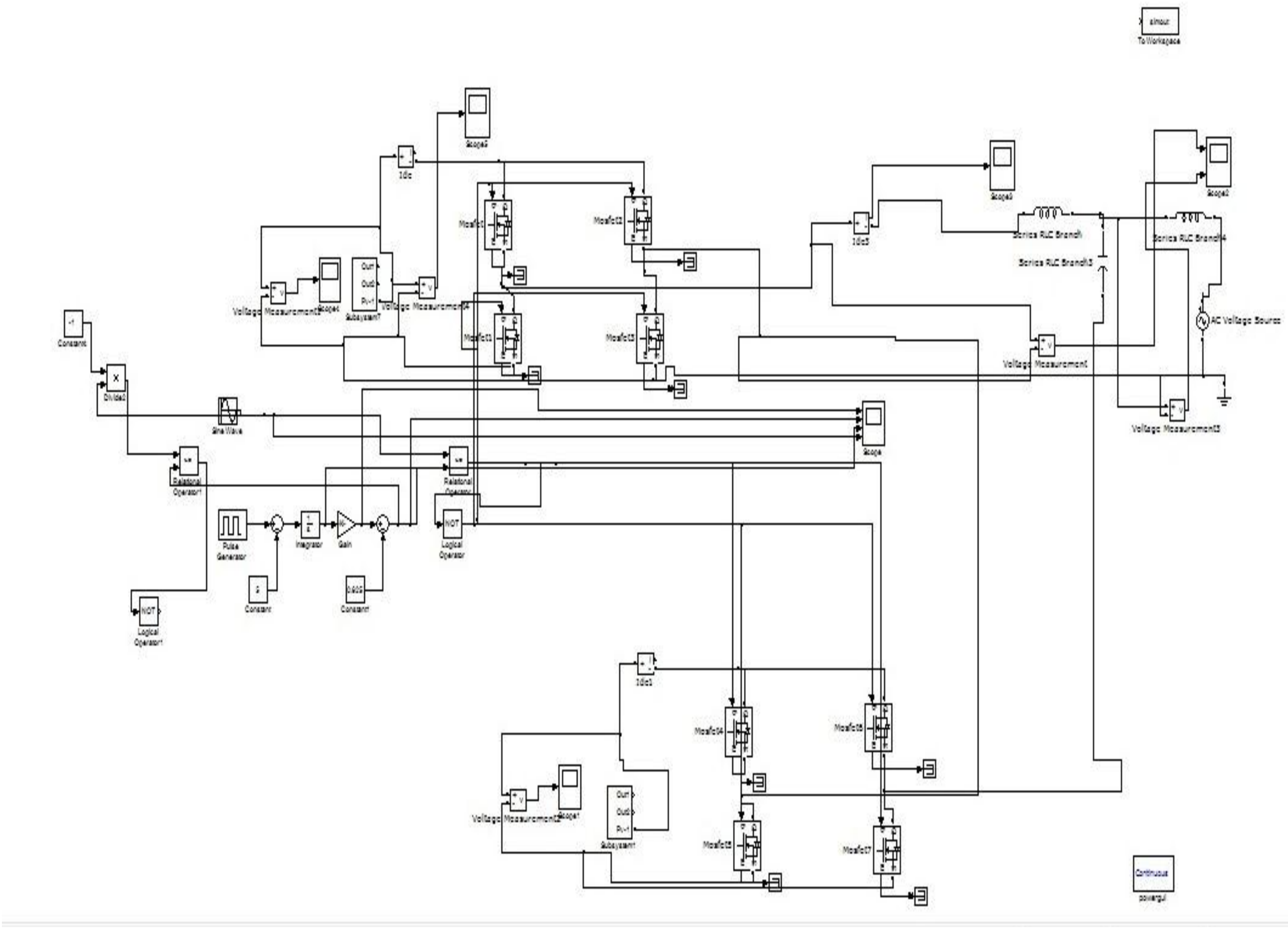

Fig 32: Overall circuit

The PV array block:

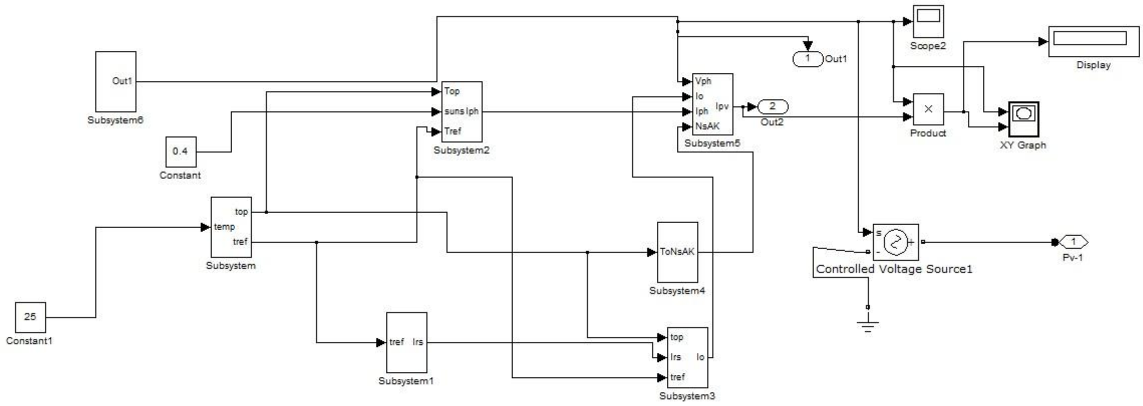

Fig 33: PV array block

The dc link voltage is obtained in Simulink as below. It should remain constant throughout so as to obtain the desired voltage level control required by the system.

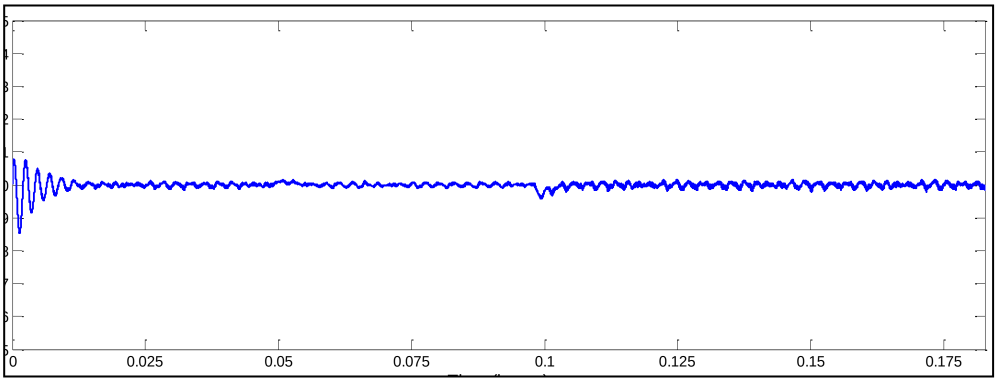

Fig 34: Dc link voltage

4.4 CONCLUSION:

The PV array results obtained have been verified as per the program and also its working situations discussed earlier.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 CONCLUSION:

The PV array is simulated in the open circuit case and its characteristics are obtained. The MPPT method used here is found to be more efficient than other MPPT methods and hence better results are obtained using the incremental conductance method. the simulation results obtained of the inverter voltage and DC voltage are as per the system design and are having minimum harmonics.

5.2 FUTURE WORK:

The MPPT method used in this system can be varied with other methods and a better efficient tracking can be obtained. The various current control methods and dc voltage controllers used are not of very high efficiency and can be replaced with other types to get a better result.

REFERENCES

[1] Welter P. Power up, prices down, grid connected inverter market survey (Leistung rauf, Preise runter, MarkituÈ bersicht netzgekoppelter Wechselrichter, in German). PHOTON-das Solarstrom Magizin (German Solar Electricity Magazine) 1999;3:48±57.

[2] Calais M, Agelidis VG. Multilevel converters for single-phase grid connected photovoltaic systems Ð an overview. In: Proceedings of the IEEE International Symposium on Industrial Electronics. Pretoria, South Africa, vol. 1, 1998, p. 224±9.

[3] Martina Calaisa,*, Vassilios G. Agelidisb Michael S. Dymondc, “A cascaded inverter for transformerless single-phase grid-connected photovoltaic systems, Renewable Energy, volume 22, Issues 1-3, January – March 2011, page 255-262.

[4] Al-Mohamad, Ali. "Efficiency improvements of photo-voltaic panels using a Sun-tracking system." Applied Energy 79, no. 3 (2004): 345-354.

[5] Rob W. Andrews, Andrew Pollard, Joshua M. Pearce, “The Effects of Snowfall on Solar Photovoltaic Performance ”, *Solar Energy* **92**, 8497 (2013).

[6] "Small Photovoltaic Arrays”. *Research Institute for Sustainable Energy (RISE), Murdoch University*. Retrieved 5 February 2010.

[7] Reflective Coating Silicon Solar Cells Boosts Absorption Over 96 Percent Scientificblogging.com (2008-11-03). Retrieved on 2012-04-23.

[8] Solar Cells and their Applications Second Edition, Lewis Fraas, Larry Partain, Wiley, 2010,ISBN 978-0-470-44633-1, Section10.2.

[9] Yuhua Cheng, Chenming Hu (1999). "§2.1 MOSFET classification and operation". *MOSFET modeling & BSIM3 user's guide*. Springer. p. 13. ISBN 0-7923-8575-6

[10] U.A.Bakshi, A.P.Godse (2007). "§8.2 The depletion mode MOSFET" Electronic Circuits. Technical Publications. pp. 8–2. ISBN 978-81-8431-284-3 Power Electron., vol. 9, no.3, pp 676-684.

[11] Hanju Cha and Trung-Kien Vu ,”Comparitive analysis of low pass output filter for single- phase grid-connected photovoltaic inverter “,Department of Electrical Engineering, Chungnam National University, Daejon, Korea.

[12] E-Habrouk M., Darwish M.K., Mehta P., "Active power filters: a review", IE Proceedings-Electric Power Applications, Vol. 147, Iss. 5, pp. 403-413, 2000

[13] Akagi H., "Active harmonic filters", Proceedings of the IEEE, Vol. 93, Iss. 12, pp. 2128-2141, 2005

[14] Marco Liserre, Frede Blaabjerg, Steffan Hansen, “Design and Control of an LCL-Filter-Based Three-Phase Active Rectifier”, IEEE Transactions on Industry Application, Vol. 41, No. 5, pp. 1281-1291, 2005.

[15] IEA-PVPS, *Cumulative Installed PV Power*, Oct. 2005. [Online]. Available: http://www.iea-pvps.org

[16] M. Shahidehpour and F. Schwartz, “Don’t let the sun go down on PV,” *IEEE Power Energy Mag.*, vol. 2, no. 3, pp. 40–48, May/Jun. 2004.

[17] G. Saccomando and J. Svensson, “Transient operation of grid-connected voltage source converter under unbalanced voltage conditions,” in *Proc. IAS*, Chicago, IL, 2001, vol. 4, pp. 2419–2424.

[18] I. Agirman and V. Blasko, “A novel control method of a VSC without ac line voltage sensors,” *IEEE Trans. Ind. Appl.*, vol. 39, no. 2, pp. 519–524, Mar./Apr. 2003.

[19] R. Teodorescu and F. Blaabjerg, “Flexible control of small wind turbines with grid failure detection operating in stand-alone or grid-connected mode,” *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1323–1332,Sep. 2004.

[20] R. Teodorescu, F. Blaabjerg, U. Borup, and M. Liserre, “A new control structure for grid-connected LCL PV inverters with zero steady-state error and selective harmonic compensation,” in *Proc. IEEE APEC*, 2004, vol. 1, pp. 580–586.

[21] S.-H. Song, S.-I. Kang, and N.-K. Hahm, “Implementation and control of grid connected ac–dc–ac power converter for variable speed wind energy conversion system,” in *Proc. IEEE APEC*, 2003, vol. 1, pp. 154–158

[22] H. Zhu, B. Arnet, L. Haines, E. Shaffer, and J.-S. Lai, “Grid synchronization control without ac voltage sensors,” in *Proc. IEEE APEC*, 2003,vol. 1, pp. 172–178.

[23] C. Ramos, A. Martins, and A. Carvalho, “Current control in the grid connection of the double-output induction generator linked to a variable speed wind turbine,” in *Proc. IEEE IECON*, 2002, vol. 2, pp. 979–984.

[24] S. Fukuda and T. Yoda, “A novel current-tracking method for active filters based on a sinusoidal internal model,” *IEEE Trans. Ind. Electron.*, vol. 37, no. 3, pp. 888–895, 2001.

[25] X. Yuan, W. Merk, H. Stemmler, and J. Allmeling, “Stationary-frame generalized integrators for current control of active power filters with zero steady-state error for

current harmonics of concern under unbalanced and distorted operating conditions," *IEEE Trans. Ind. Appl.*, vol. 38, no. 2, pp. 523–532, Mar./Apr. 2002.

[26] R. Teodorescu and F. Blaabjerg, "Proportional-resonant controllers. A new breed of controllers suitable for grid-connected voltage-source converters," in *Proc. OPTIM*, 2004, vol. 3, pp. 9–14.

[27] D. Zmood and D. G. Holmes, "Stationary frame current regulation of PWM inverters with zero steady-state error," *IEEE Trans. Power Electron.*, vol. 18, no. 3, pp. 814–822, May 2003.

[28] Keller G, Krieger T, Viotto M. Module oriented photovoltaic inverters: a comparison of different circuits. In: Conference Record of the 24th IEEE PV Specialists Conference. vol. 1, 1994, p. 929±32.

[29] Fujimoto H, Kuroki K, Kagotani T, Kidoguchi H. Photovoltaic inverter with a novel cycloconverter for interconnection to a utility line. In: Conference Record of the 1995 IEEEIndustry Applications 30th IAS Annual Meeting. vol. 3, 1995, p. 2461±7.

[30] M.Liserre, A. Dell'Aquila, F.Blaabjerg *"Design and control of a three-phase active rectifier under non-ideal operating conditions" IEEE Transactions on power electronics*, 2002 Pp: 1181 – 1188